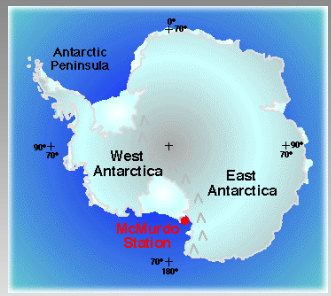
The Antarctic Ice Borehole Probe



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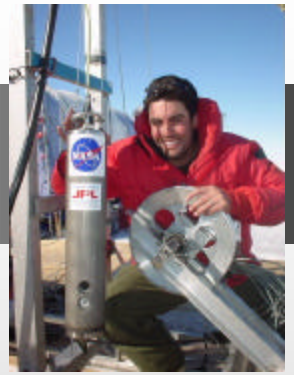
Project Description



- **The Antarctic Ice Borehole Probe mission was a glaciological investigation, performed in November 2000-January 2001**
- **It acquired visible-light images and video in several (up to) 1.2km hot-water drilled holes (West Antarctic ice sheet) at Ice Stream C**
- **Objectives of the probe were to observe ice-bed interactions with a downward looking camera, and ice inclusions and their structure, including hypothesized ice accretion, with a side-looking camera**

For Info, Pics and Videos...

http://helios.jpl.nasa.gov/~behar/JPLAntIceProbe.html

Project Sponsors

- **NASA Code Y**
- **Jet Propulsion Laboratory**
  - **Center for In-Situ Exploration & Sample Return**
  - **Div. 32, Earth & Space Sciences**
  - **Div. 34, Avionic Systems and Technology**
  - **Div. 35, Mechanical Systems Engineering & Research**
  - **Div. 38, Observational Systems & Software Systems**
- **Caltech**
  - **Geological and Planetary Sciences Division**
- **NSF**
  - **Office of Polar Programs**

Project Team

- **Project Name**
  - **Ice Sheet Measurements for Climate Study**
- **Instrument Team**
  - **Frank Carsey, Earth & Space Science Division**
  - **Arthur “Lonne” Lane, Earth & Space Science Division**
  - **Alberto Behar, Avionic Systems & Technology Division**
  - **Barclay Kamb, Caltech, Geological & Earth Science Division**
  - **Hermann Engelhardt, Caltech, Geological & Earth Science Division**

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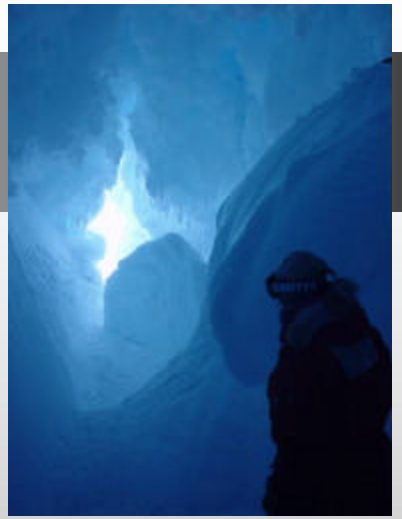

- **Introduction**
- **Project Goals**
- **Probe Specifics**
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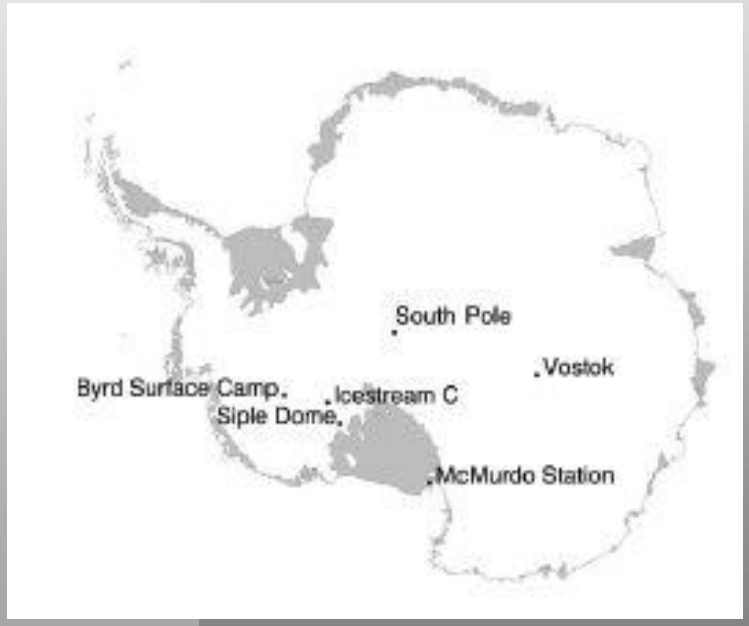
- **Future Work**

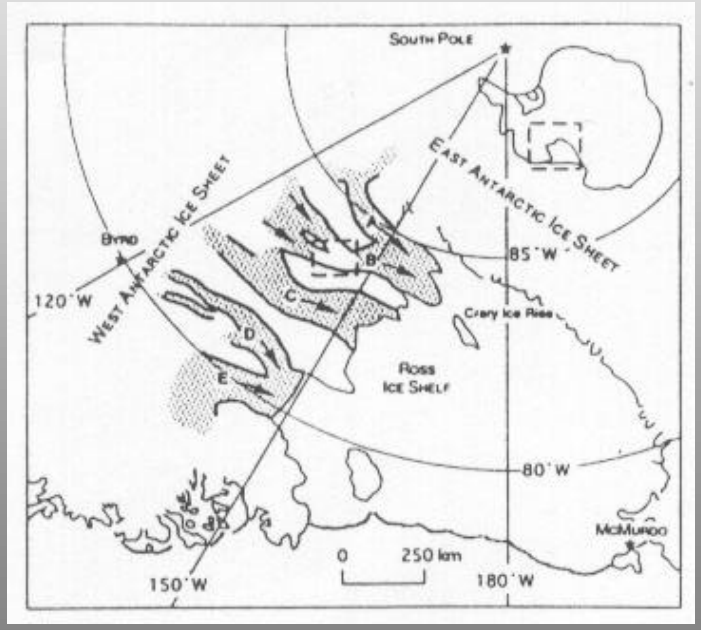
Introduction

- **New technology & innovations are being developed and used for science in extreme environments such as thick ice sheets**
- **Results are useful in study of long-term climate change**
- **This talk focuses on current fieldwork that, for the first time ever, returned video images from under the West Antarctic Ice Sheet**
- **Other related current work includes:**
  - JPL Cryobot
  - JPL Lo'ihi Underwater Thermal Vent Probe

Location

- Ice Stream C, West Antarctica





Glaciological Objectives

Overall - goal to obtain observational evidence for cause of rapid flow of great ice streams in West Antarctic Ice Sheet (WAIS)

Before - Previous boreholes at Ice Streams B and D were used to measure physical conditions and collect sample materials at the base where lubrication for rapid ice stream motion (~ 1m/day) is expected

Now - Ice Stream C poses a special problem, it has stopped streaming (~150 years ago) even though basal material and physical conditions are scarcely different from Ice Streams B and D

Focus - to study Ice Stream C intensely to reveal what physical conditions might differ from B and D to have caused the stoppage

Result - Understand the ice-stream control mechanisms to reliably assess the possible contribution of ice streams to ice-sheet dynamics brought about by either climate change or internal instabilities

Glaciological Objectives

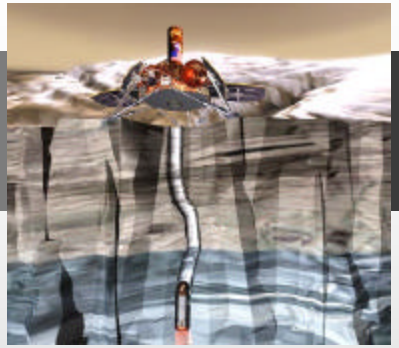
Location - To study the variation in basal conditions in the transition from unfrozen to frozen bed along a traverse from ridge BC to a "sticky spot" at Ice Stream C where velocity drops from 20m/yr to 3m/yr

Method - Ice Borehole probe observations of the basal zone, including ice structure, rock debris in basal ice, the basal water-conduit system and the basal till

Other Investigations:

- In-situ shear strength measurements of basal till with torvane instrument
- Ice core sampling through bubbly to clear ice (clathrate) transition and debris laden ice
- Piston coring to collect sediment cores for later laboratory analysis
- Testing novel rock drill assembly where frozen bed or bed rock prevented piston coring
- Long term measurements of temperature profile and basal water pressure

Technology Objectives

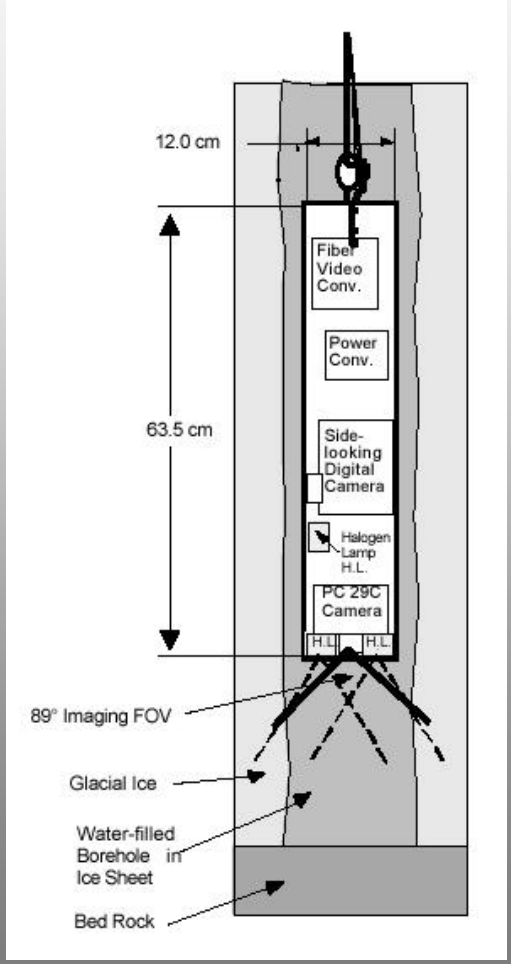


- **This endeavor serves as a stepping stone in the development of technology to acquire scientific data in extreme ice and liquid environments**

- **In future, other projects can use technology developed for such scientific objectives as:**
  - Earth paleocirculation and ice dynamics
  - Lake Vostok exploration
  - Europa ocean in-situ exploration
  - Mars polar exploration
  - Climate history
  - Titan pre-biotic exploration
  - Exobiology

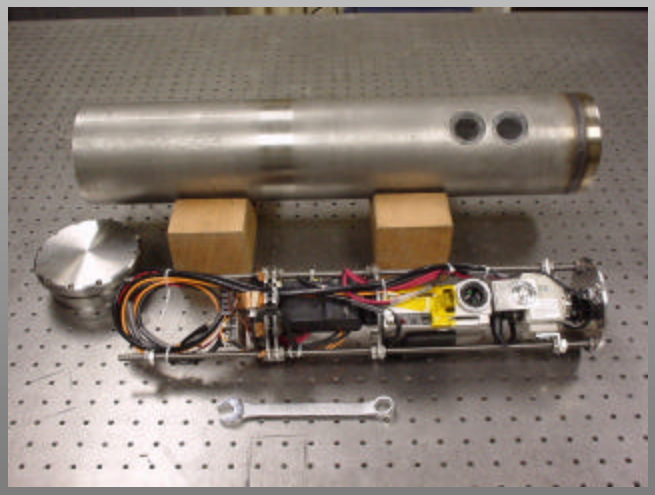
Probe Specifics - Probe

- **Imaging**
  - 1 Digital Side Camera, 1/4” CCD, 345K pixel, 10x optical zoom, 3.3 – 33 mm focal distance
  - 1 Down hole Camera, 1/3” CCD, 470K pixels 470 vertical line resolution, 2.4mm focal distance
- **Lights**
  - 3 Halogen 3W Video Lights
- **Signal Transmission**
  - 2 Video/Fiber Transmitters, LED Based, Intensity Modulated, 850nm, 26 db loss budget
- **Power**
  - 2 Power Converters, 300VDC in, 6 & 12VDC out



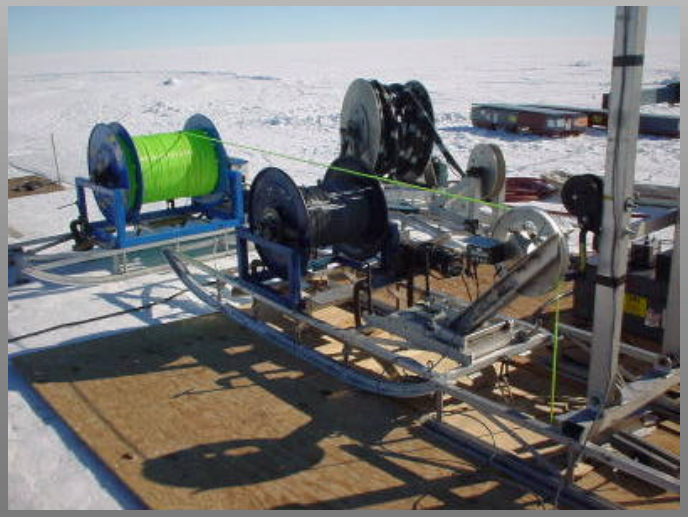
Probe Specifics - Probe

- **Stainless Steel Pressure Housing, 12 cm diameter, 63.5 cm length**
- **2 quartz windows on side 1 for camera and 1 for halogen bulb**
- **1 quartz window on bottom for two down looking lights and one camera**
- **Internal frame consists of two threaded rods that hold a series of plates which support the cameras, lights, and power converters**



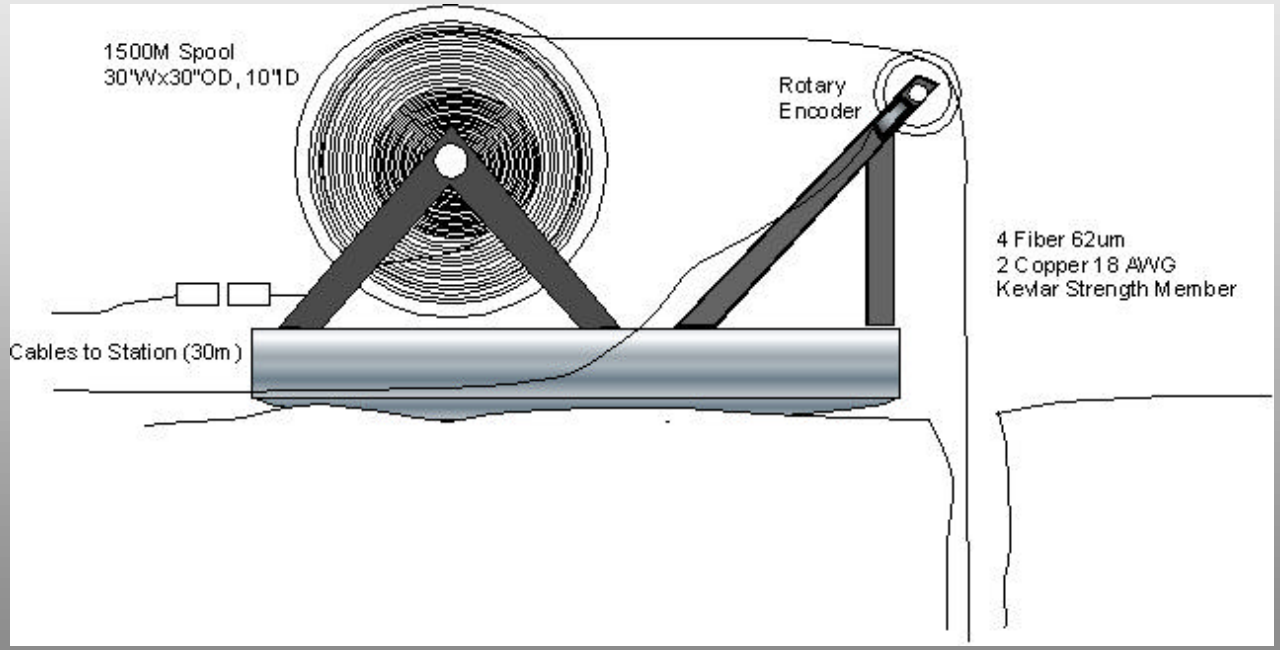
Probe Specifics - Cable

- **Cable contains 4 multi-mode, FDDI grade, 62.5/125 micron, fibers encased in stainless steel tube with gel filled water block**
- **Fiber tube is bundled with twisted pair 18 AWG copper wire, an inner jacket, kevlar (1000 lb) strength member and polyurethane outer jacket**
- **Length: 1.6 km, Rating: -40C to 90C, 1000V, Weight in air: 60lbs/1000'**
- **Finished OD 0.327", Min Bend Radius 4.5"**



Probe Specifics - Reel System

- **Split reel design provides 100m continuous connections**
- **Shieve mounted torque sensor measures tether load**
- **Shieve mounted rotary encoder, depth overlay on video signal**
- **3 Phase reel motor allows up to 1m/s deployment**



Probe Specifics - Ground Station

- **Primary**
  - **2 DV Recorders for Video uplink**
  - **Panasonic Video Monitor**
  - **IR Side Camera Remote**
  - **Video Fiber Receiver**
  - **Reel Sensor Data Recorder**
  - **Probe 70-300V Power Supply**
  - **Video Distribution Amp**
- **Data Post-Processing**
  - **Sony PC L630**
  - **CD-RW Disk Drive**
- **Diagnostic Tools**
  - **Video Test Generator**
  - **Waveform Monitor**
  - **Osc. Scope, DMM, Fiber Tools**

Pressure Vessel Tests - USNL

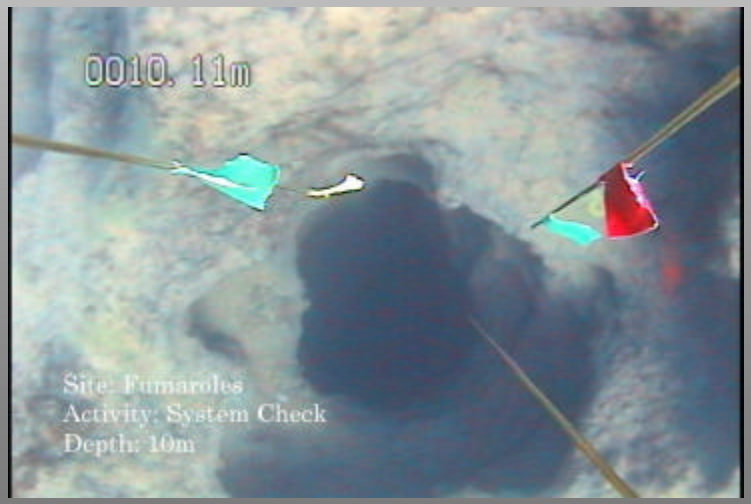
- **Housing Tested to 2 km depth**
- **Location: USNL, Port Huyneme, CA**
- **Stainless Steel Pipe, 12cm diameter**
- **Survived 1.5 km for 5 cycles at 1° C**
- **Bottom image shows quartz fracture at 2km**

Probe Imaging Tests - Caltech

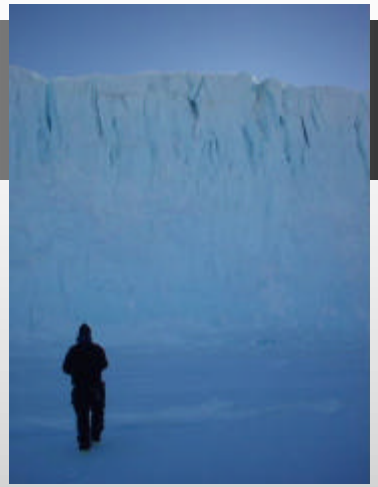
- **March-August 2000**
- **To determine:**
  - **functionality of polarized imaging to observe ice grains and gas bubble/dust grain inclusions**
  - **In-lab system resolution and verification**
  - **Temperature survivability –8° C**
- **Measurements made in 0.5 m boreholes created in Caltech lab ice**
- **System functionality was verified**
- **Polarized light imaging not functional when borehole is water-filled due to similar index of refraction between ice and water**

Field System Test - Crater Lake

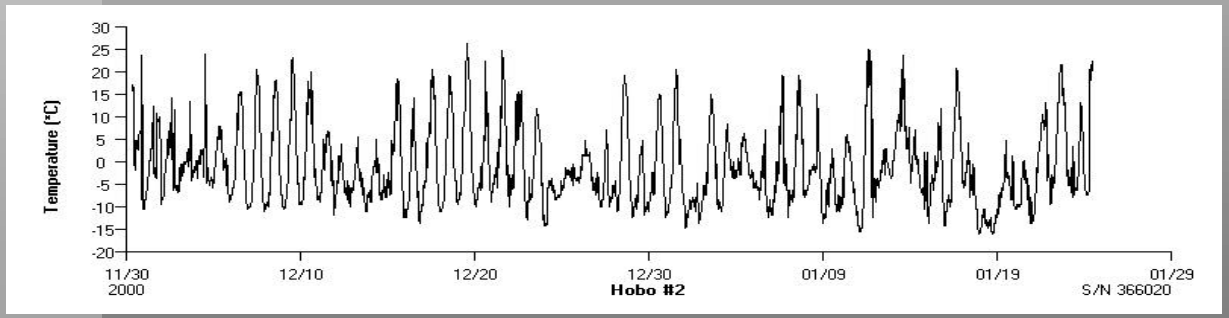
- Field Test, August 2000
- Crater Lake, Oregon
- Deepest Lake in N. America
- Bottom: 500m & 3° C
- Crystal clear, still water



Antarctica - Specifics

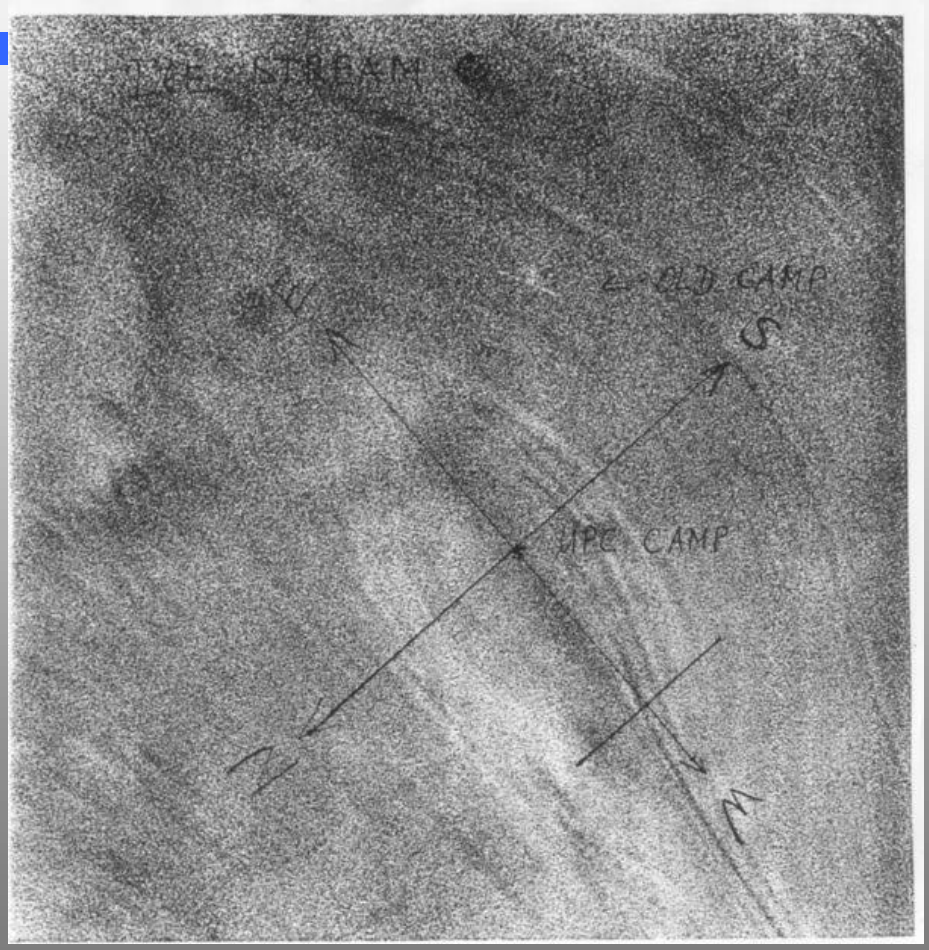


- **Coldest, highest, windiest, driest continent**
- **Summer NSF season from Nov 1-Jan 31 each year**
- **Ice Stream C is 860km from South Pole**
- **Average annual temperature ~ -25C, Ice Stream C**
- **Field season Max 0° C, Min -18° C, Avg. ~ -12° C**
- **Below is temp. from a data logger placed outside, high points skewed due to direct sunlight exposure**



Ice Stream C - Surface Flow

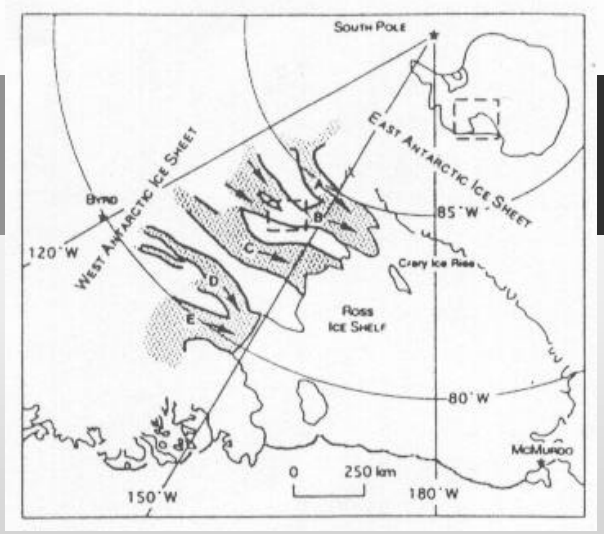
- **Area in center (termed "sticky spot") has slowed movement ~150 years ago**
- **Main camp at center**
  - 82º 22' S, 136º 24' W
  - ~500 m elevation,
  - ~800km to South Pole
  - ~700km to McMurdo
- **Ice Stream C '97 camp in SE quadrant**
- **4 Drill Sites; at camp and 7, 3 and 1 km south of base camp**



Ice Stream C - Specifics

- **Objective I: to reveal on an observational basis the mechanism of rapid ice-streaming motion as a guide to theoretical models of the ice-stream phenomenon in the West Antarctic Ice Sheet (WAIS)**
- **Objective II: Study basal processes and conditions at the bottom of Ice Stream B, C, and D**
- **2000-01 Season: Ice Stream C chosen to provide comparison with B and D on an ice stream whose rapid motion slowed down greatly ~150 years ago**
- **With the hope that models developed will be able to predict reliably the future behavior of WAIS as a component of global change and the effect of world wide sea levels**

Ice Stream C - Specifics



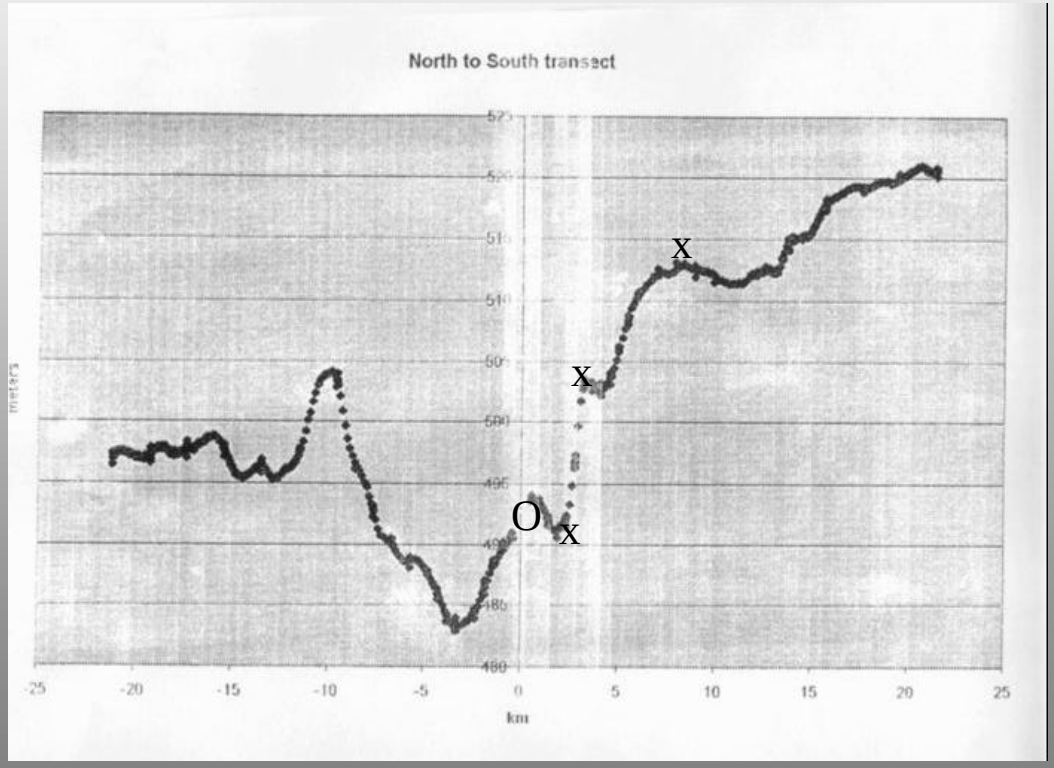
- **Picture shows W. Antarctic ice streams A-E (shaded) in relation to Ross Ice Shelf and South Pole**
- **Stream Flow Rates:**

• Ice Stream B	>1 m/day	
• Ice Stream D	~1 m/day	
• Ice Stream C Drill Site #2	6 cm/day	7km distance from Base
• Ice Stream C Drill Site #3	~2 cm/day	3km distance from Base
• Ice Stream C Drill Site #1	0.02 cm/day	Base location

- **Expected Properties**
  - **Initial borehole water level 30m, after break through ~100m**
  - **Water drop at breakthrough usually takes ~1-3mins, sometimes +30 mins**
  - **Basal debris calculated to be 0.3-10m thick from base of ice**
  - **Basal water system gap calculated to be on the order of mm**
  - **Basal water system was never actually witnessed**

Ice Stream C - Surface Elevation

- **Area in center “sticky spot” is at lowest point**
- **0 - Main Camp**
- **X - Drill Sites along the S**
- **Elevation change ~1m/km**

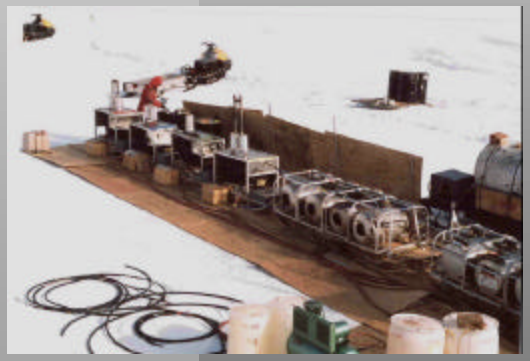


Science Logistics

- **Team: 11 on science team, 5 on camp support staff**
- **Equipment: Drilling Rig, Borehole instruments, two 20KW generators, 6 barrels of antifreeze, 220 gal mogas + 1000 gal JP-8 per week**
- **Drilling and probe equipment moves on ski mounted modular structures towed by tracked vehicles**
- **Team members travel between camp and drill site by snowmobiles**
- **Cargo Estimate: 89,265 lbs**
- **UNAVCO GPS profiles taken to locate drill sites and measure velocity profiles through our borehole sites parallel and perpendicular to the ice stream flow**

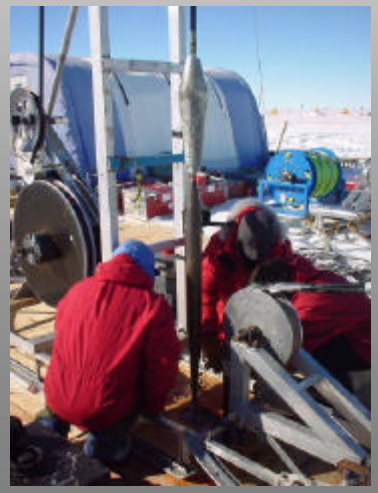
Drill Camp - Setup

- **Transport by LC-130 to Ice Stream C**
- **Cargo unloaded by Forklift**
- **Drill equipment mounted on sledges**
- **Transferred to drill site by tractor/skidoo**
- **Drill site setup with heaters/pumps co-linear**
- **Accommodation setup in mountain tents**

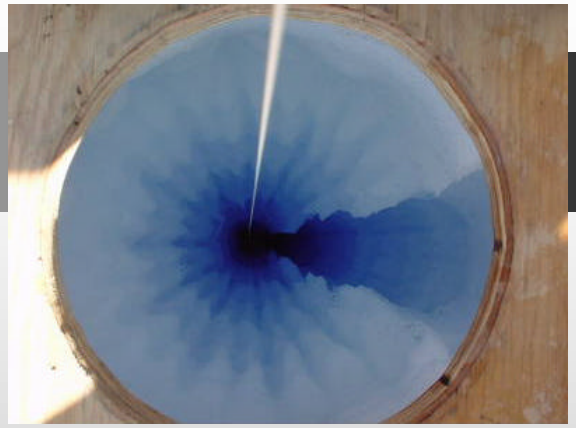


Drill - Specifics

- **Technique: Hot-water jet drilling**
- **Drill segment is 7.6 cm wide x 1 m long**
- **Maximum 3 segments long**
- **Thermal power 480kw**
- **~20 hours of drilling for 1km, 10 cm borehole**
- **Reamed for ~ 12 to 24 hrs, in stages, up to 17 cm**
- **4 independent heater/pump systems combined to feed hose**
- **20 l/min per system, 80 l/min total**
- **Water Temp: 80ºC at entry**
- **30ºC at nozzle exit 1 km down**

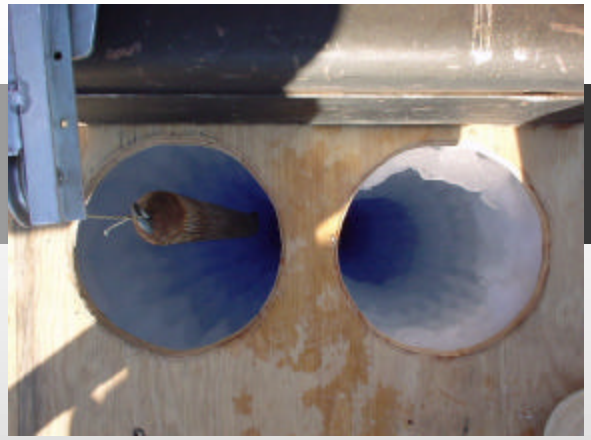


Borehole - Specifics



- **Boreholes to base of ice 1000-1200 m deep**
- **Water filled holes ~10cm diameter after drilling, 17cm after reaming**
- **Instruments deployed for ~4 hours without freeze in**
- **Temperature gradually increases from –20C subsurface to ~ pressure melting point at bottom**
- **Well hole drilled (15cm away, 130m deep) to recycle melt water**
- **Freeze in takes 1-2 days in upper half, months at bottom**
- **Temperature equilibrium for entire borehole can take months**
- **4 drill sites, ~3 boreholes each, 1 at each site for probe**

Borehole - Findings



- **Common Borehole Features**
  - **Debris layers found above the base of ice, (up to 26m above base)**
  - **Bubbly to clear ice transition zone found at each site**
  - **Rocks oriented similarly with a flat side down**

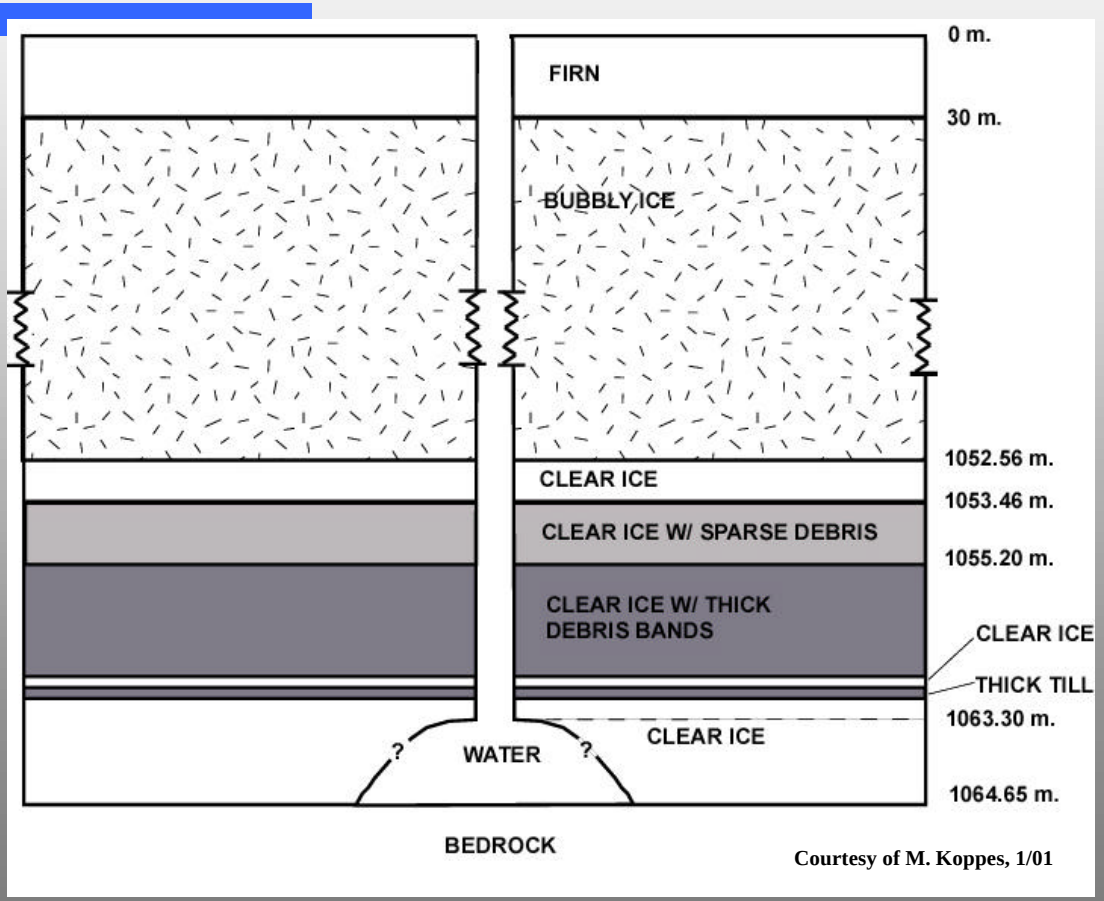
- **Drill Site Borehole Occurrences**
  - **Drill Site #1 – No breakthrough, turbid water**
  - **Drill Site #2 – Breakthrough, small gap, semi-clear water, slow out flow**
  - **Drill Site #3 – Breakthrough, large cavity, extremely clear, fast out flow**
  - **Drill Site #4 – Slow breakthrough, no probe investigation performed**

- **Important question about the Drill Site #3 basal cavity:**

  "Is it a general feature or specific to the shear margin?"

Drill Site #3 - Borehole Profile

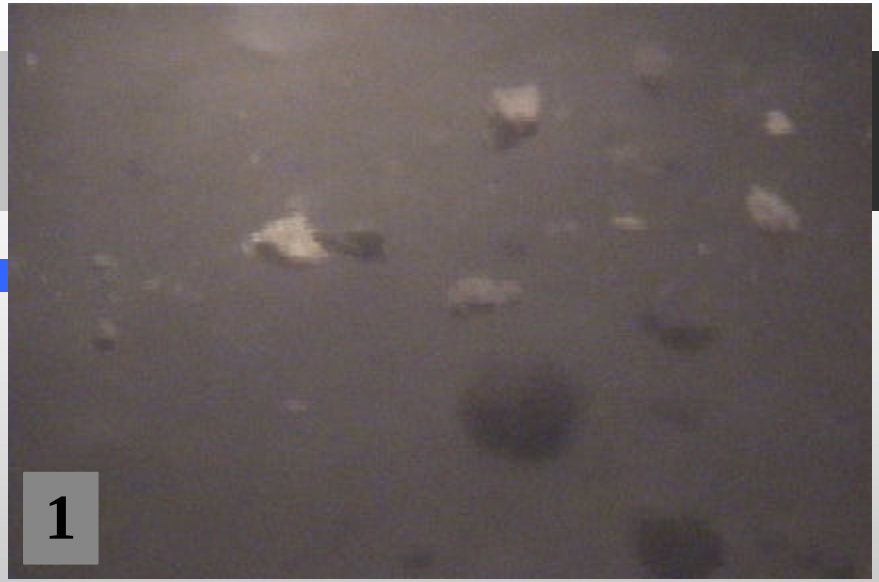
- **Profile encountered at Ice Stream C, Drill Site #3**
- **Former Sub-glacial hydrological models predict basal gaps on the order of 1-2mm (Kamb)**
- **Basal Cavity found was 1.4 meters deep**
- **Location a good analogy for Europa Missions**

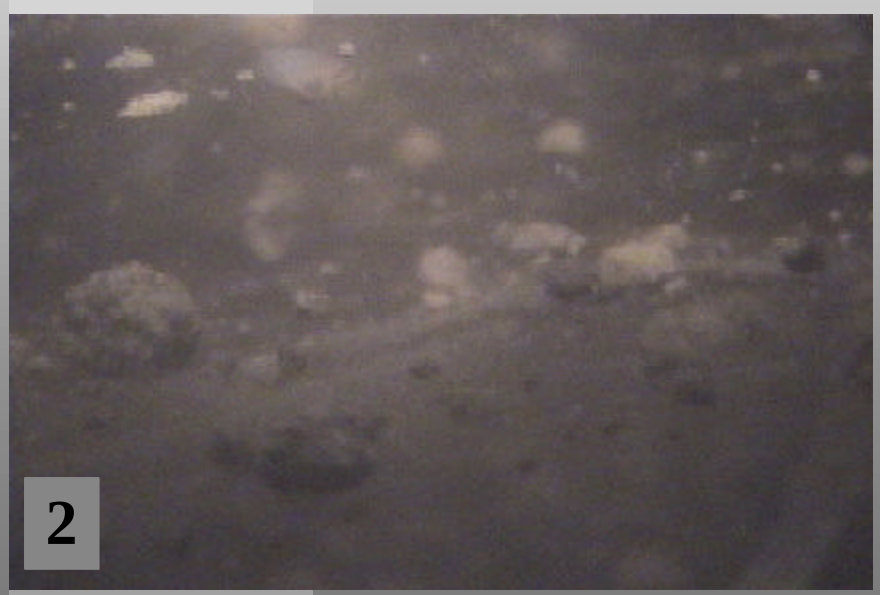


Courtesy of M. Koppes, 1/01

Drill Site #1

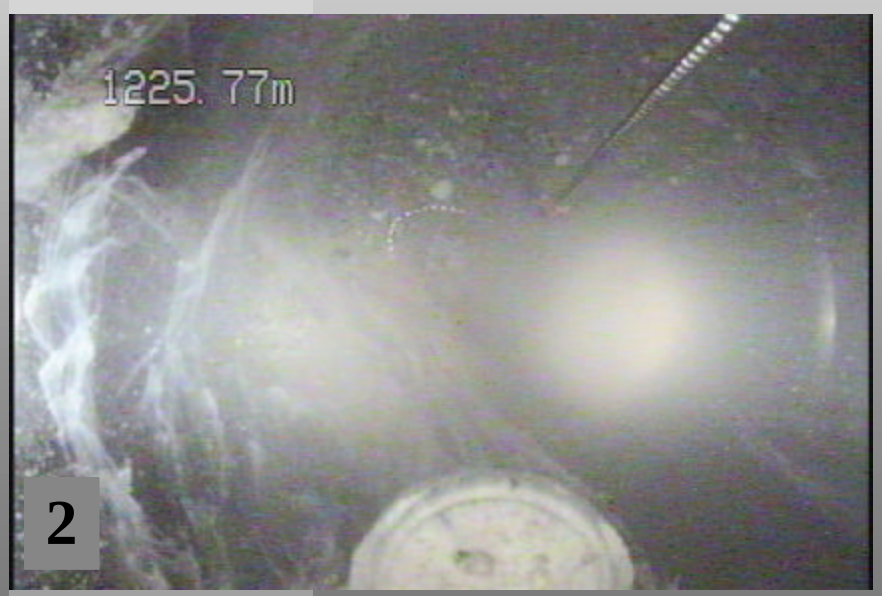
- **High turbidity no breakthrough to disperse fine sediment by flushing them out**
- **Sediment aggregations and rocks floating in clear, bubble-free ice**

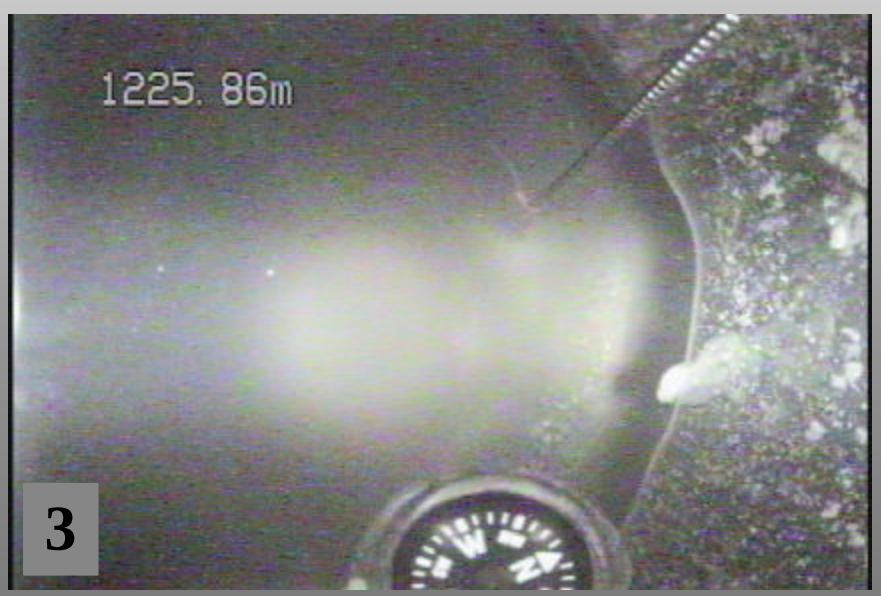




Drill Site #2

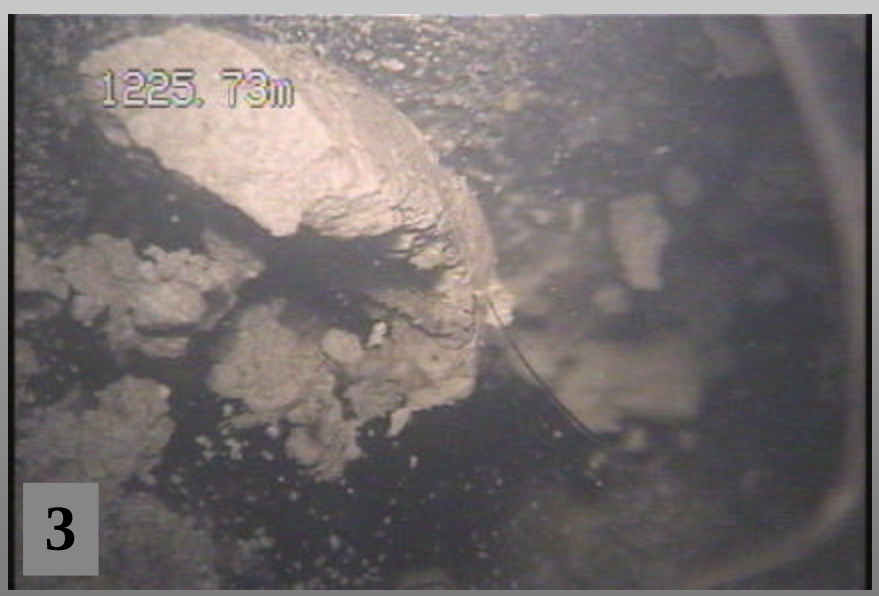
- **Deep borehole with water breakthrough**
  1. **Layering of debris seen on side**
  2. **Turbidity escaping into basal gap**
  3. **Basal edge seen clearly**





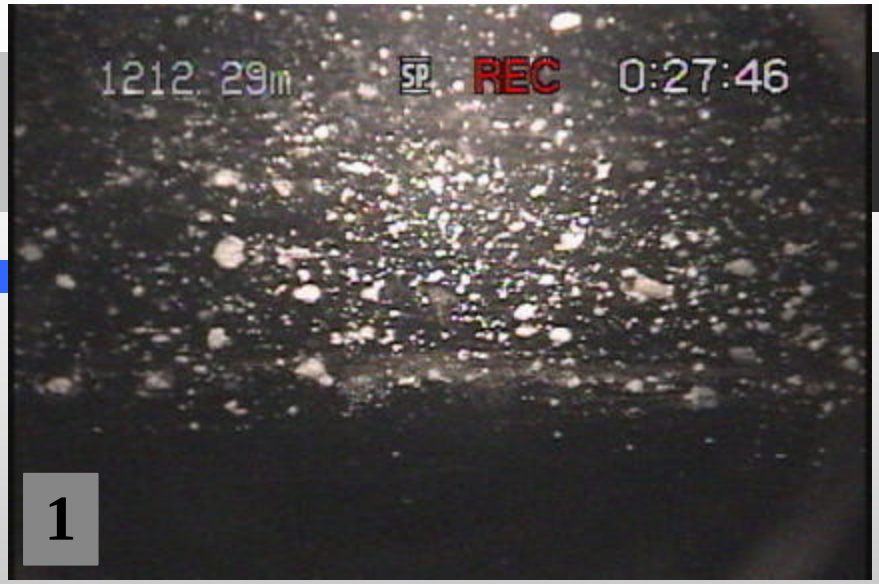
Drill Site #2

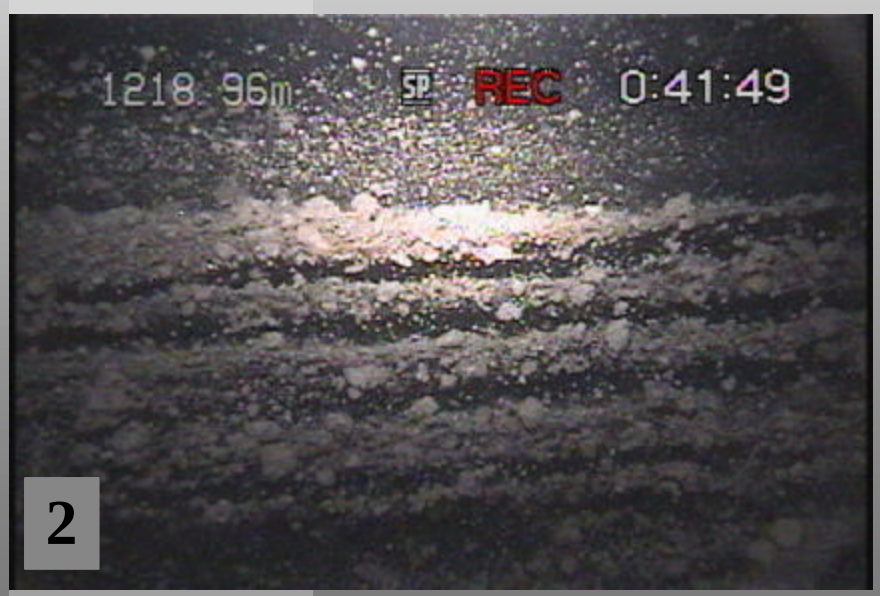
- **Basal rocks floating in ice**
  1. **Rock in ice ~ 3 cm across**
  2. **Rocks returned by piston coring**
  3. **Rock partially melted out of borehole**

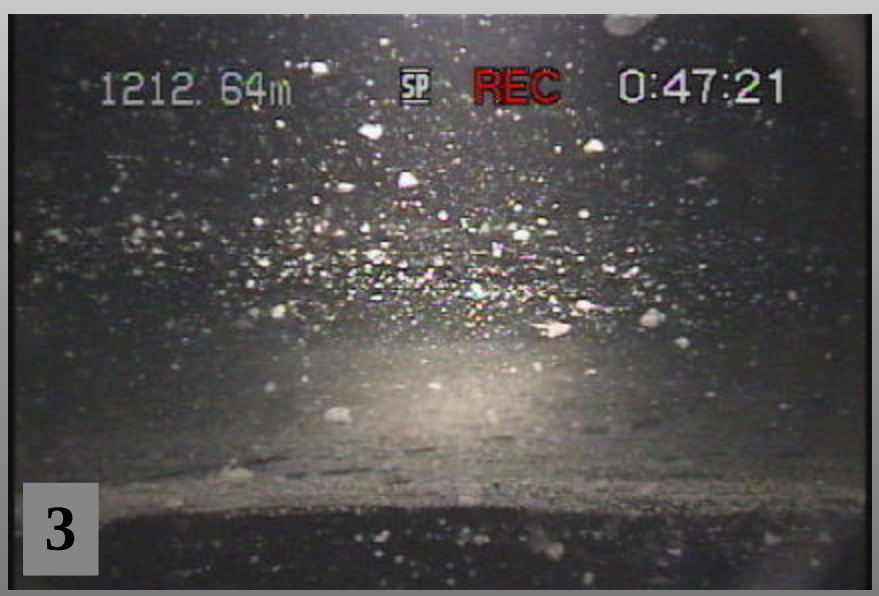


Drill Site #2

- **Debris layers show historic freeze-on**
  1. **Transition from debris-laden to clear**
  2. **Tight layering of basal sediment**
  3. **Single thin layer of debris**

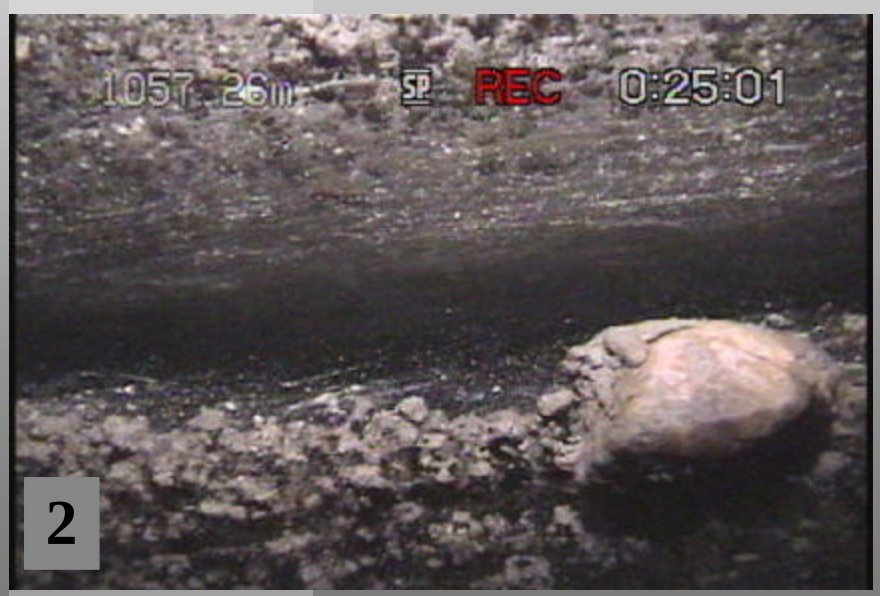






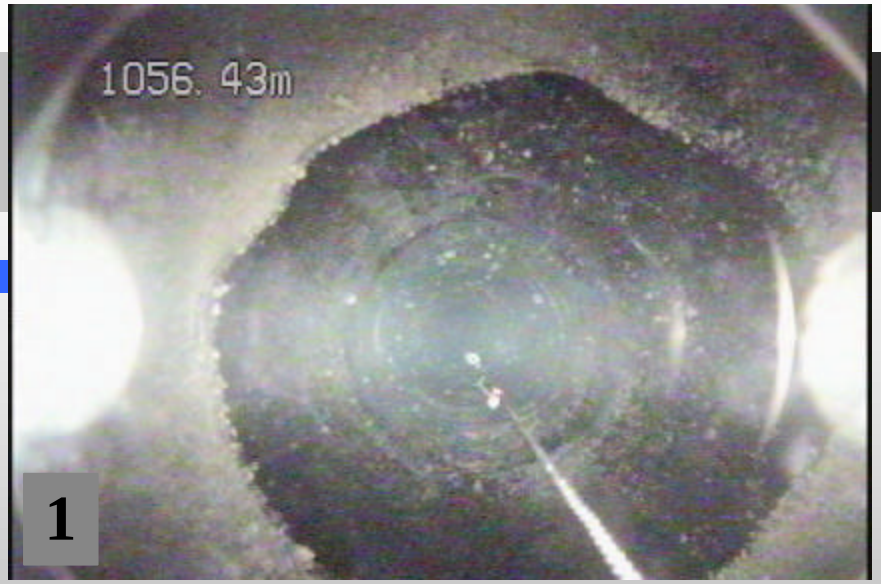
Drill Site #3

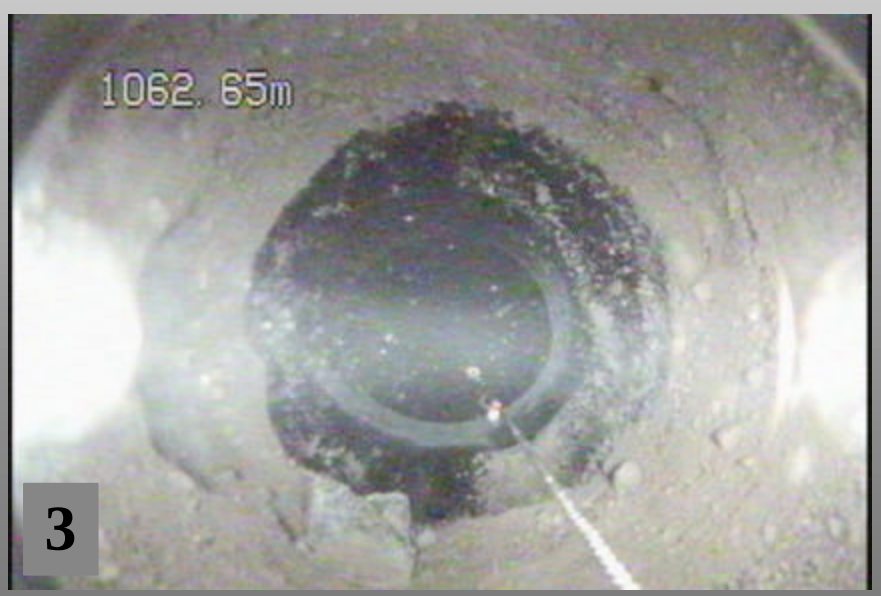
- **Layering of Debris in Clear Ice**
  1. **Several layers seen through borehole**
  2. **Clear ice between 2 debris layers**
  3. **Tight concentration of layers**



Drill Site #3

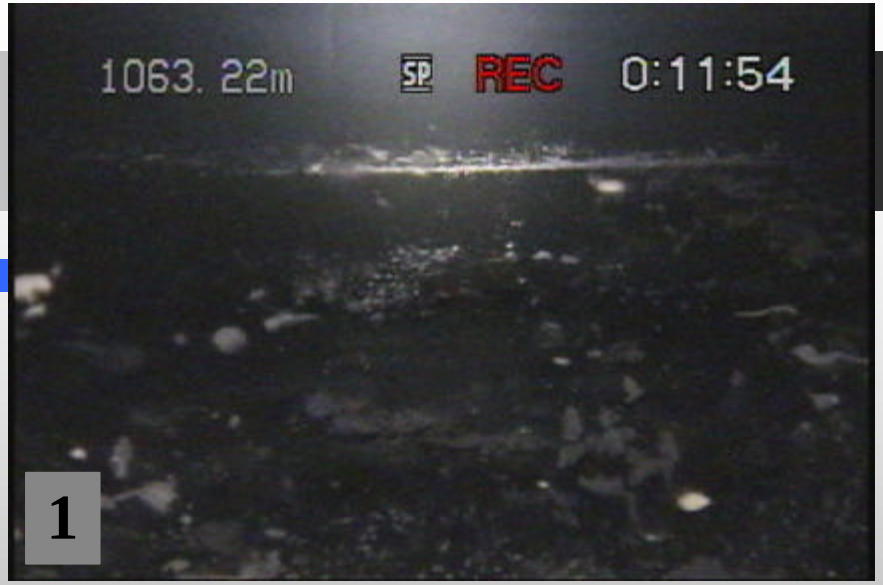
- **Base of ice above 1.4 m deep cavity**
  1. **Debris layer floating in ice**
  2. **Rock partially melted out of wall**
  3. **Base of stream with clear bottom ice**

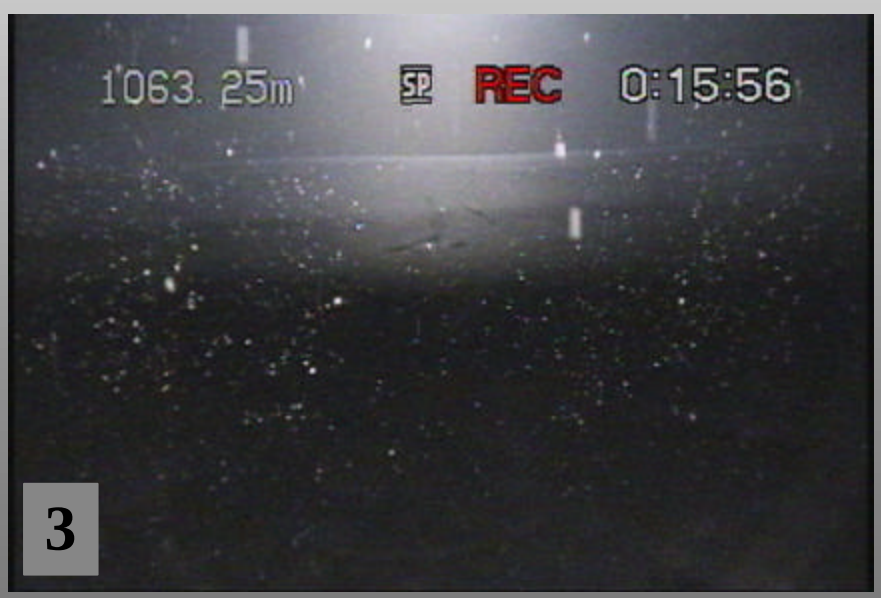




Drill Site #3

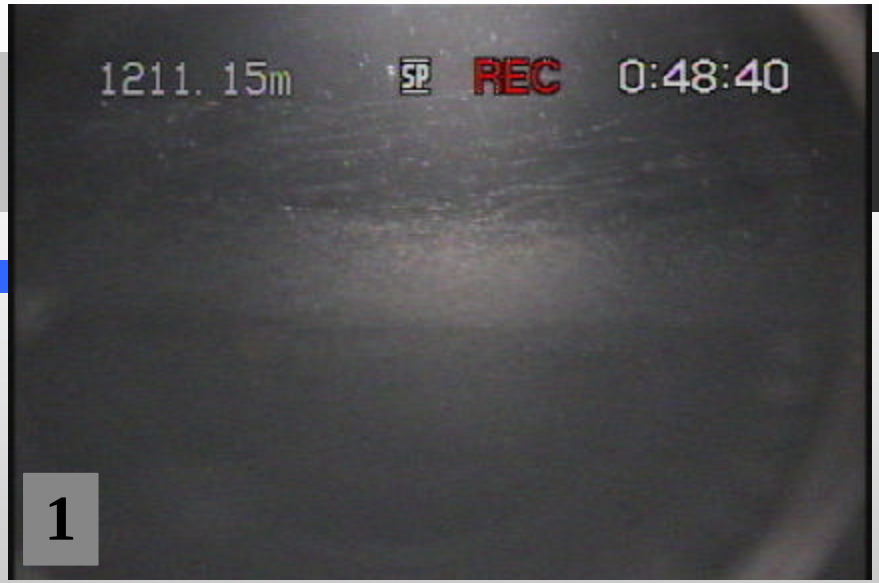
- **Base of Ice Above Water 1.4m deep**
  1. **Clear ice layer to water interface**
  2. **Ice crystal structure at base of ice**
  3. **Debris flow from borehole into cavity**

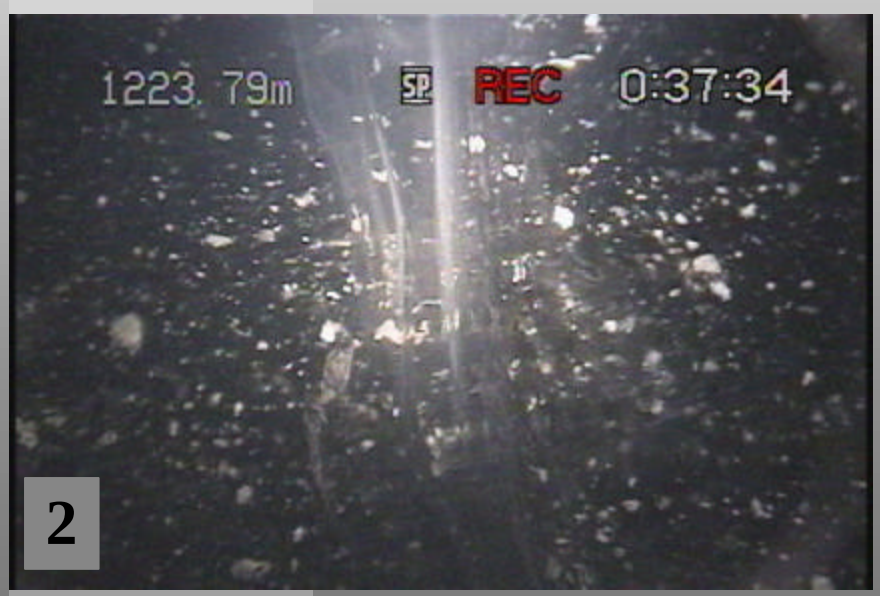


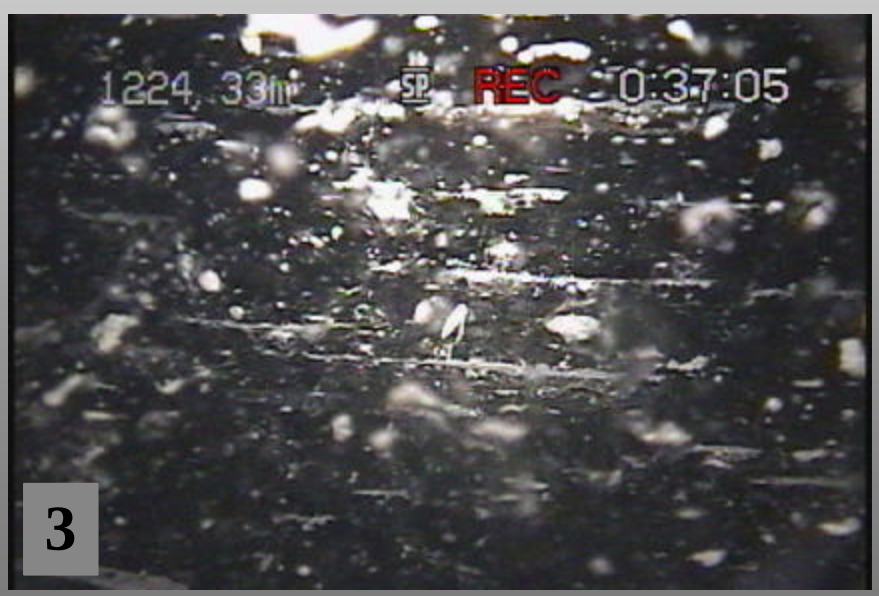


Mixed Images

- **Miscellaneous basal images**
  1. **Bubbly to clear ice transition**
  2. **Unknown features in clear ice**
  3. **Common horizontal debris orientations**

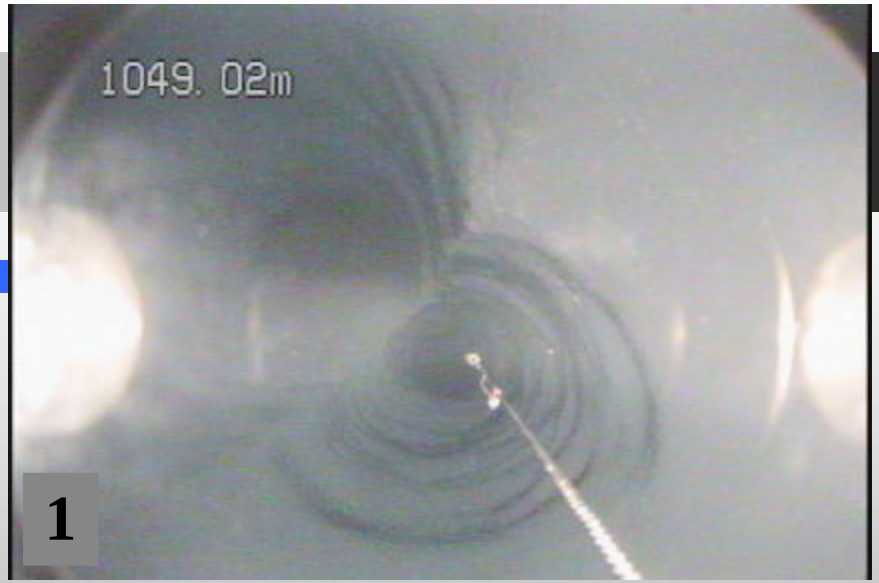


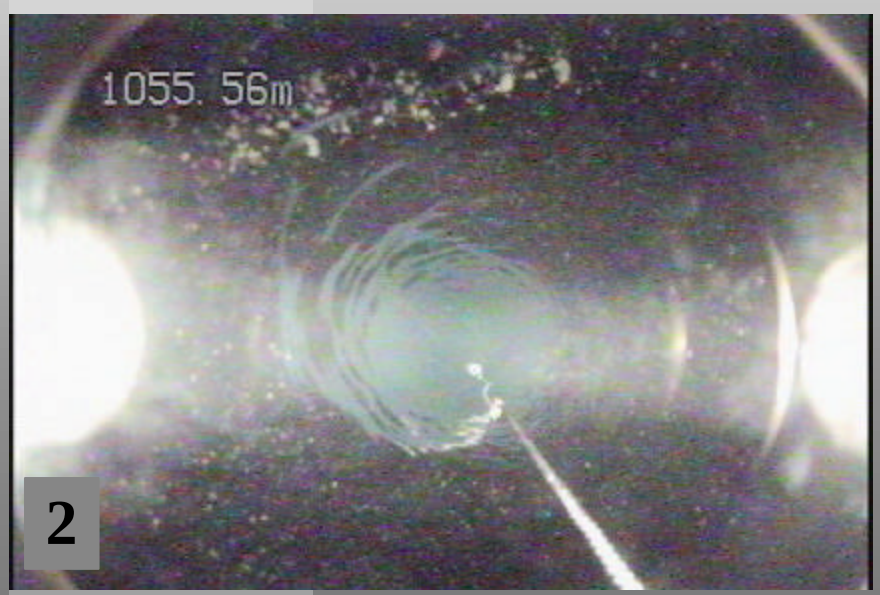


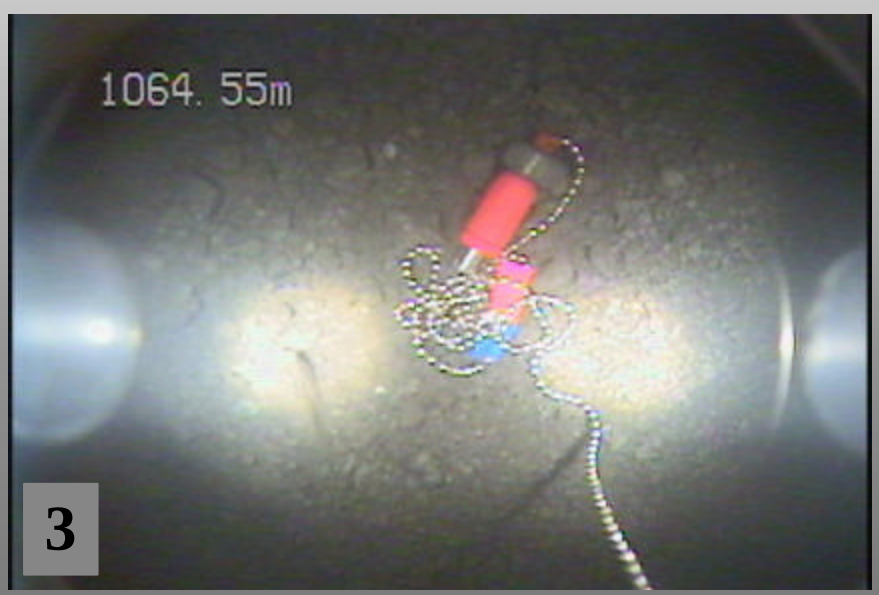


Mixed Images

- **Miscellaneous basal images**
  1. **Primary & ice coring borehole**
  2. **Borehole Ice Wall**
  3. **Basal view with debris melted out of wall**





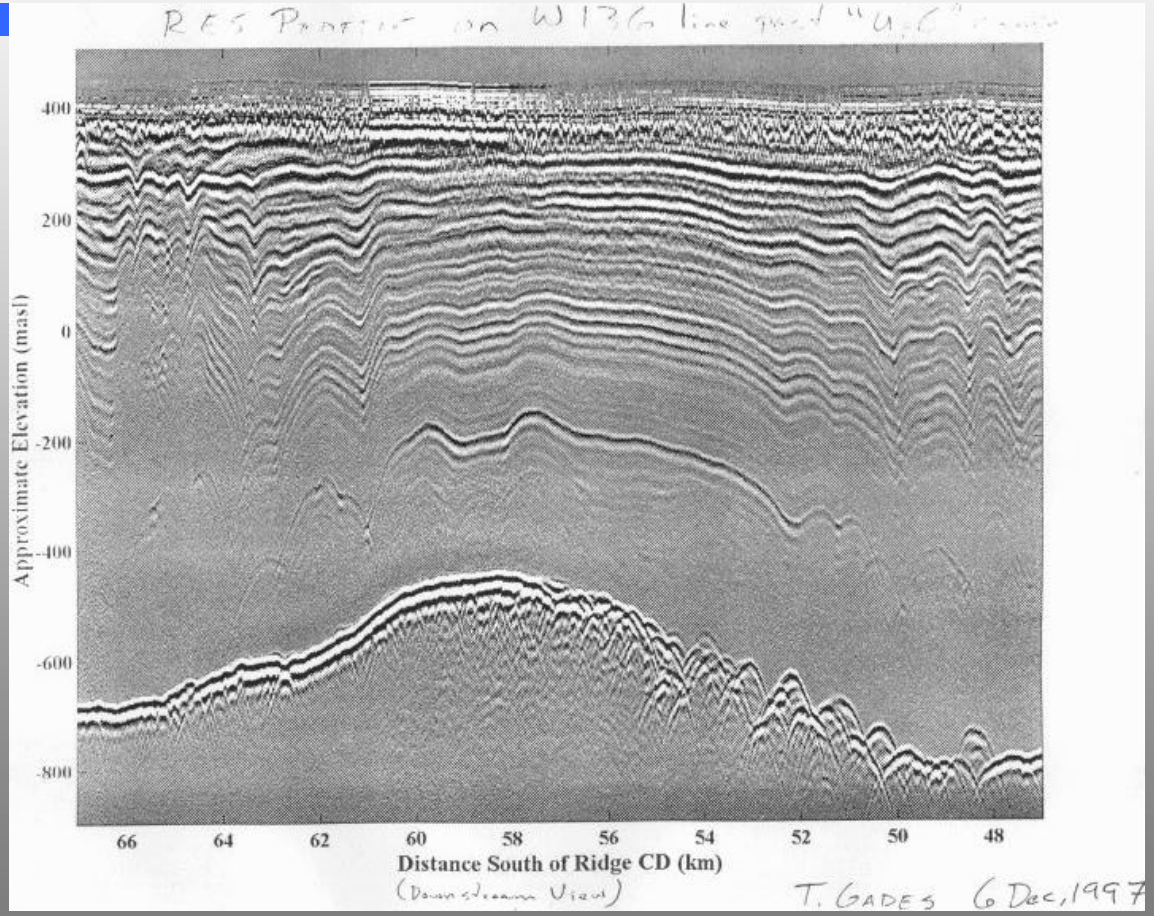


Isochron Horizon - Investigation

- **Test to search for isochronal horizon layers in ice**
- **Horizons of ice formed from snow falling after major volcanic activity**
- **Expected Attributes:**
  - Thickness: Few mm in scale
  - Appearance: cloudy
  - Depth: Layers in lower 1/3 where higher temps cause increased brine volume & light scattering
- **Interests:**
  - To see if we can find these layers optically
  - In layer structure, thickness and any other aspect of the ice co-located with the layers
  - Layers contain larger concentrations of sulfates in the form of sulfuric acid
  - May prove to be a significant nutrient supporting sub-glacial biochemical weathering processes
- **Should appear in radar record due to a mix of conductivity, density, and crystal orientation**

Isochron Horizon - Radar Profile

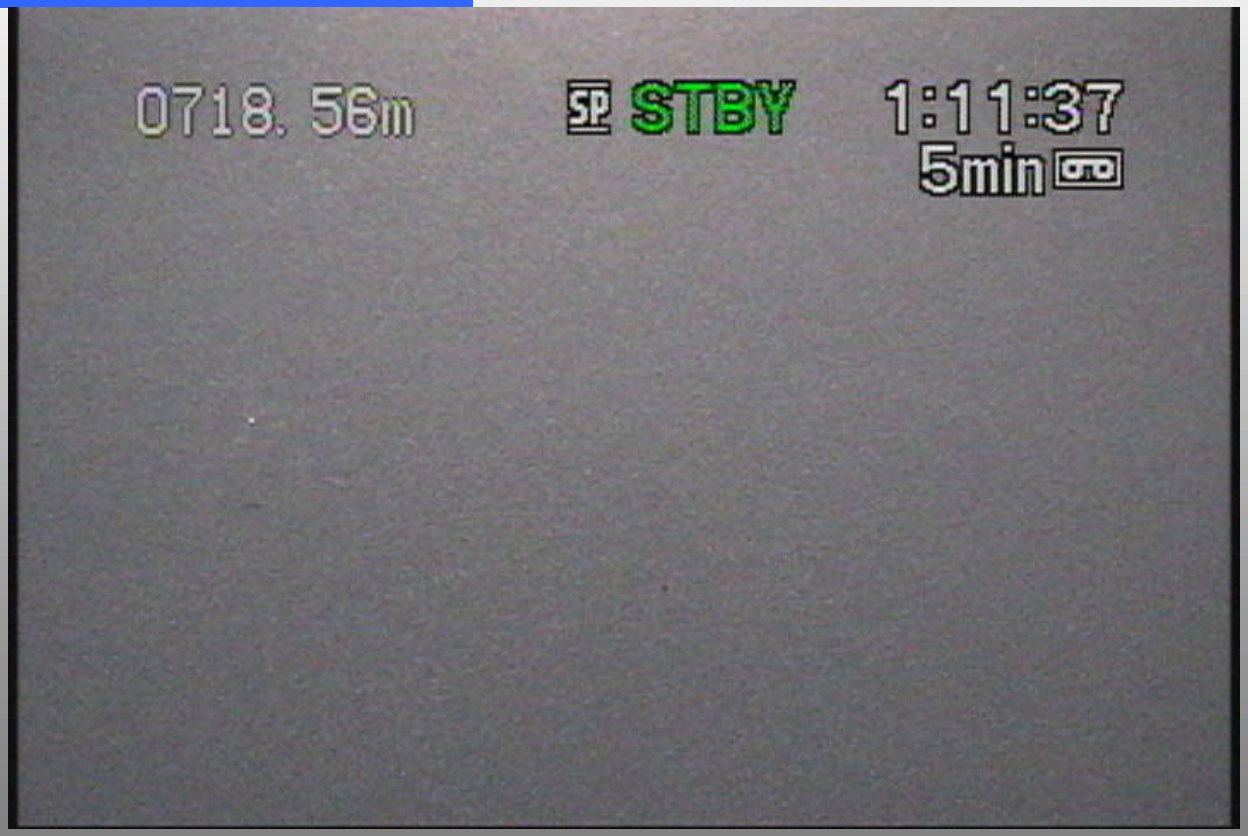
- **Sharp layer appears on radar scans at 7-800 m depth**
- **This area was searched using the side camera view**
- **Scan rate of 1 m/min**



Isochron Horizon - Debris Layer

- **Scan detected black particles of debris at a depth of 718m depth**

- **Technique useful for layer investigation together with ground penetrating radar**

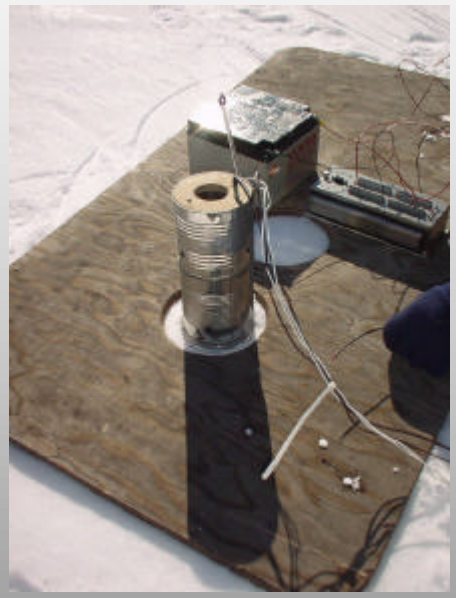


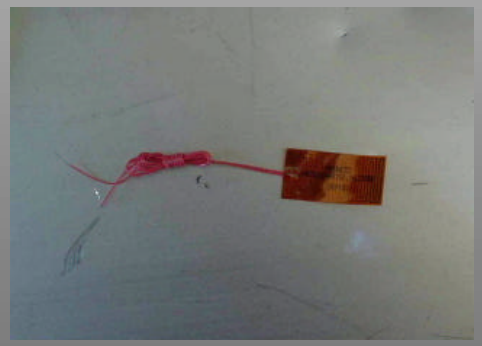
Cryobot Test - Antarctica

- **Two Runs on 12/2/00**
- **Passive Heating Element System**
- **Snow Temp: –10 to 15° C, 0-1.5m deep**

- **Test #1:**
  - Heating Element with 9 Ù inline resistor
  - Avg. Heating Element Temp: 38.5° C
  - Velocity 1.1 m/hr
  - Depth Reached: 1.2m after 65 mins

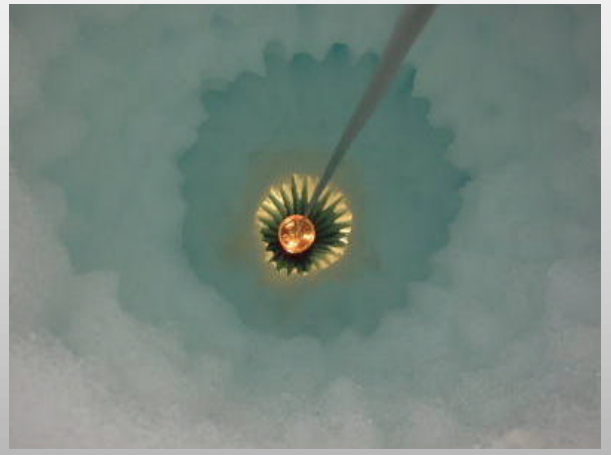
- **Test #2:**
  - Heating Element with no inline resistance
  - Avg. Heating Element Temp: 96.8° C
  - Velocity: 3.30 m/hr
  - Depth Reached: 1.1m after 23 mins





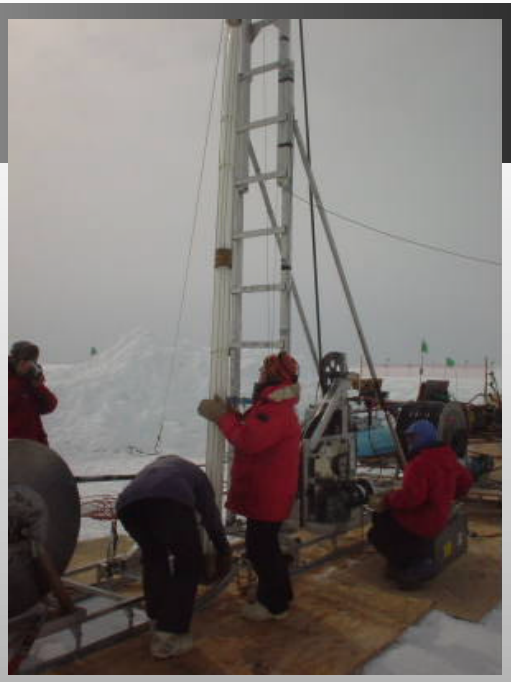
Dual Borehole Light Tests

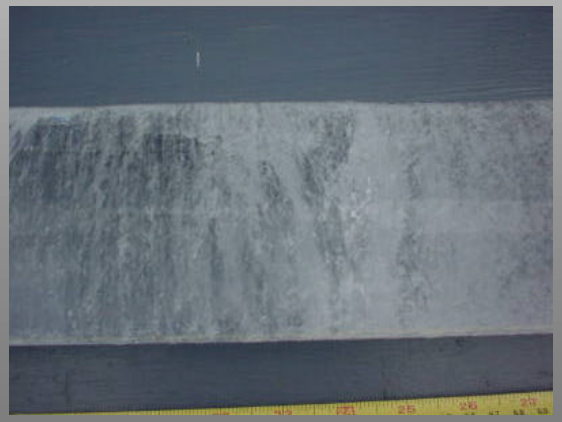
- **Test attempting to looking at light transmitted through ice instead of reflected**
- **Light Unit was constructed**
  - Three, 30W bulbs, Co-planar, 120° apart
- **2nd borehole created 1m apart**
- **First 100m depth studied**
- **Motion of light unit detected by still probe**
- **Not much information gathered**
- **Technique still under development**
- **Separate Occurrence**
  - **Lower picture shows a 2nd borehole at 1km**

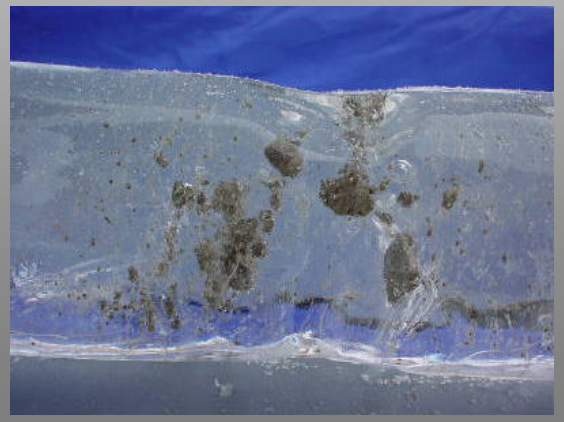


Ice Coring - Results

- Ice Coring at 750 and 1050 m depth
- First time cores are returned with debris
- 28°C water used to drill core
- Cores are 10cm diameter by 4m long
- Shown is bubbly ice, bubbly/clear ice transition and debris laden ice







Conclusions

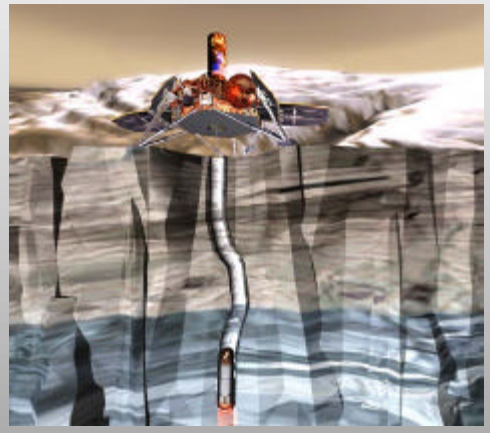
- **Glaciological investigations using the Antarctic Ice Probe were extremely successful**
- **Long-term climate change investigations still abound on earth for this type of technology**
- **Further development needed in expanding suite (chemical, biological and physical) and resolution of sensors**
- **Careful design rules must be adhered to in designing for extreme environments**
- **Antarctica is a strong analog for future planetary ice surface missions**

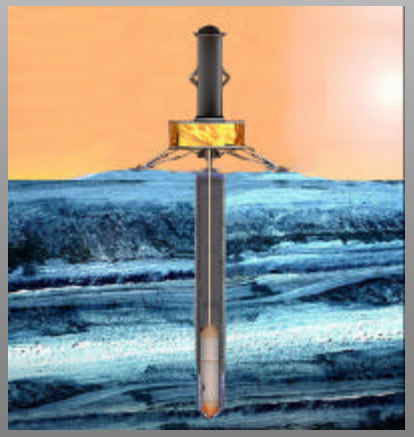
FOR MORE INFO...

http://helios.jpl.nasa.gov/~behar/JPLAntIceProbe.html

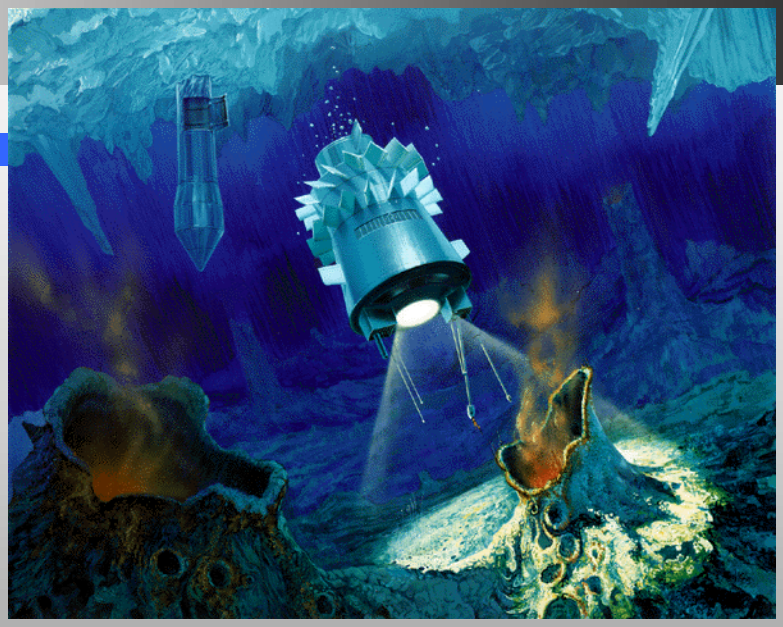
Future Work

- Crater Lake investigations
- UV fluorescence sensor inclusion
- Microscopic studies of dust in ice
  - long-term climate studies & micrometeorites
- Detachable swimming robot
- Image resolution increase
- Lake Vostok exploration
- Mars polar cap explorer
- Europa cryobot

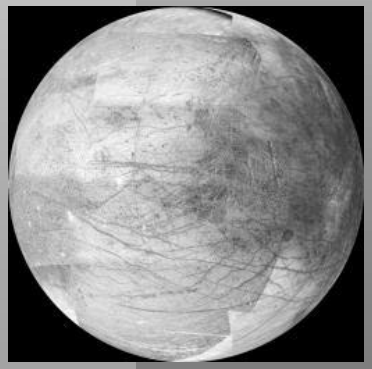


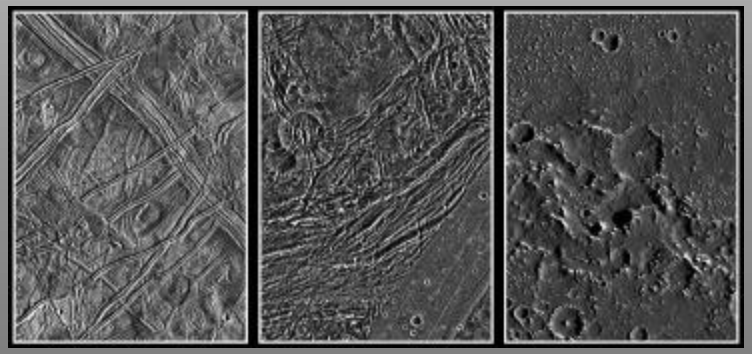


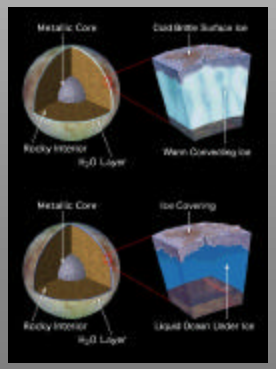
Europa Cryobot



- Proposed ice-penetrating Cryobot and Hydrobot to explore the ice-covered ocean on Jupiter's large satellite, Europa
- Cryobot would melt through the ice cover and deploy a hydrobot, a self-propelled underwater vehicle to analyze the chemical composition of the ice/water in a search for signs of life







Low Budget Science